A REVIEW OF CONTINUUM LEPTON PAIR PRODUCTION BY HADRONS

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I. Introduction

My task today is to give an overview of recent developments in the area of continuum lepton pair production and in particular to review the contributions submitted to this conference. Since this field is young and still evolving, the physics issues may not be as widely recognized as in some other areas discussed at this conference. For this reason I will begin with a brief comparison of lepton pair production by hadrons and the closely allied field of deep inelastic lepton scattering from hadrons. The latter is a venerable area of research and certainly no stranger to this series of conferences.

(a) Relation to Deep Inelastic Scattering

The process of inclusive lepton pair production is described schematically in Fig. 1a where the two initial state hadrons are shown interacting to produce a final state lepton pair and a recoil hadron system. The most economical way to couple the lepton pair to the interacting hadrons is through a virtual timelike photon and as we shall see later the data are very suggestive of this coupling. This process is directly analogous to inelastic lepton scattering, shown in Fig. 1b, where now one lepton of the pair is in the initial state and the pair couples through a spacelike photon (or vector boson for ν). The weak coupling too must contribute to lepton pair production, it does so at a very tiny level for the kinematic range of existing experiments.

For the processes shown in Fig. 1 the real physics to be learned is in the interaction of the virtual photon with the hadronic system. In one case the probe is timelike while in the other it is spacelike. There are, however, some other important distinctions between the two processes.

In lepton scattering at a known incident energy only a single final state particle is detected so that if lepton polarizations are neglected, two kinematic variables can specify the final state. A popular pair is Q^2 and ν. The cross section is written in terms of 2 structure functions (3 for neutrino scattering) which can depend only on the two final state variables and the incident energy.

In pair production two particles are observed so five variables are needed to specify the final state. An experimentally convenient set is the mass (M), Feynman-x (x_F), transverse momentum (P_T) of the pair, and the direction of one of the leptons in the pair rest frame ($\cos\theta^*,\phi^*$). The cross section for the process of Fig. 1a must be written in terms of four structure functions. A convenient form is[1]:

$$\frac{Ed^5\sigma}{dx_F dM dP_T d\Omega^*} \propto W_T(1+\cos^2\theta^*) + W_L\sin^2\theta^* + W_\Delta\sin 2\theta^*\cos\phi^* + W_{\Delta\Delta}\sin^2\theta^*\cos 2\phi^* \, , \qquad (1)$$

where all dependence on θ^*, ϕ^* is explicitly shown and the W functions depend only on M, x_F, P_T and incident energy. Here W_T and W_L are structure functions associated with transverse and longitudinal virtual photon polarizations while W_Δ and $W_{\Delta\Delta}$ correspond to off-diagonal density matrix elements for the pair.

Thus lepton pair production as a probe of hadronic structure offers some features not found in lepton scattering. In particular the helicity angular distribution $d\sigma/d\Omega^*$ provides a direct way to measure the virtual photon polarization for fixed values of the other kinematic variables.

(b) Drell-Yan Production Mechanism

Simplification of this formalism occurs when a particular model is assumed for the photon-hadron coupling. In deep inelastic lepton scattering it has been fruitful to consider the photon interacting with a charged quark from the target hadron, as shown in Fig. 2a. Comparison of measurements with this model and its QCD modifications is now an active area of study.[2]

The analogous process for pair production is quark-antiquark annihilation and is often referred to as the Drell-Yan mechanism.[3] The process is shown in Fig. 2b. In this model the structure functions W_L, W_Δ, $W_{\Delta\Delta}$ are all identically zero. Corrections to the basic process such as expected from QCD lead to nonzero values for these functions. From kinematic arguments, together with the parton model, one anticipates that[1] $W_\Delta/W_T \sim O(P_T/M)$ and $W_{\Delta\Delta}/W_T \sim O(P_T^2/M^2)$.

One should note that the Drell-Yan mechanism is only expected to be valid if the annihilating quarks can be treated as free during the time of interaction. This requires the ratio $\tau = M^2/s$ to be not too small. What this means quantitatively is an experimental question. Moreover, it is known that pair production is very large in the region $\tau \to 0$ so that some alternative mechanism must contribute here.[4]

II. Recent Experiments

Let us now turn to the data. Table I shows the submissions to this conference together with recent publications. This Table updates the one given by Lederman at the Tokyo Conference.[5] The most notable change is the entry into the field of a new high statistics, high acceptance experiment by the CCOPS collaboration at the CERN-SPS. The other experiments have been reported at previous conferences and their main contributions since Tokyo are higher statistics and/or more refined analyses. This latter point should not be underestimated since this is a developing field and the most profitable ways to analyse and present the data are still evolving.

III. Evidence for the $q\bar{q}$ Annihilation Model

First we will examine the evidence for the pair production mechanism discussed above, without reference to detailed quark distribution functions. Quantitative results on hadron structure will be discussed in due course.

The relevant kinematics for $q\bar{q}$ annihilation are shown in Fig. 3. Here x_1 and x_2 refer to the fractional energy of the quark (antiquark) from the beam and target hadrons respectively. These simple relations between x_1, x_2 and the observables M and x_F follow directly from conservation of energy and momentum. However, they neglect the mass and transverse momentum of the individual quarks and cannot be expected to apply when x_1 or x_2 is very small.

(a) Strength of the Interaction. If the $q\bar{q}$ annihilation cross section is integrated over θ^*, ϕ^*, and P_T, it has the form

$$\frac{d\sigma}{dM^2 dx_F} = \frac{4\pi\alpha^2}{9M^4} h(x_1, x_2) , \qquad (2)$$

where $h(x_1, x_2)$ is a sum of products of quark and antiquark distribution functions and the coefficient of h manifests the one-photon intermediate state. The CFS group has used their measured pair production cross section together with a suitable version of equation (2) to deduce the antiquark distribution in the nucleon. The result is shown in Fig. 4 in comparison with measurements using deep inelastic neutrino scattering. The agreement of these results is remarkable, given the entirely different nature of the two experiments. The deduced quark distribution functions agree in shape over a factor of 50 variation and the absolute normalizations agree to better than a factor of 2. We shall return to this comparison for a more quantitative discussion later. The point to be made here is that since the α^2 coefficient and the $1/M^4$ variation in the cross section is implicit in the analysis, the mechanism of pair production through a single intermediate virtual photon is in good agreement with the data.

(b) Angular Distributions. The production mechanism $q+\bar{q} \rightarrow \ell^+ + \ell^-$ leads to a helicity angular distribution of $d\sigma/d\cos\theta^* \propto 1+\cos^2\theta^*$ if the quarks are on-shell and massless. This corresponds to a purely transverse intermediate photon. There is a minor ambiguity about the reference direction for measuring $\cos\theta^*$ since only the parent hadron directions are known. However, in the kinematic range of the experiments reported here the available reference vectors are all rather close together.[6]

The data have been fit to the form $dN/d\cos\theta^* \propto 1+\alpha\cos^2\theta^*$ and the results for α, submitted to this Conference, are given in Table II. A sample of the quality of recent data is shown in Fig. 5 which is taken from the CCOPS experiment. As one can see from Table II, the data, integrated over x_F and P_T, are in good agreement with the expected value of $\alpha=1.0$.

(c) Dependence on Quark Charge. Since the quark-antiquark annihilation cross section is proportional to the square of the quark's charge, one should find that in the limit of only valence quarks contributing to the production, and for an isoscalar target, that

$$\sigma(\pi^+ N \rightarrow \mu^+\mu^- + \ldots)/\sigma(\pi^- N \rightarrow \mu^+\mu^- + \ldots) = (1/3)^2/(2/3)^2$$

$$= 1/4$$

The most recent data, that from the CCOPS experiment, is shown in Fig. 6. The departure from a value of 1/4 arises from the contribution of antiquarks from the sea and from the fact that their target is not isoscalar. The lines in Fig. 6 show the expected magnitude of the ratio taking into account these effects. The result of the CCOPS group agrees with earlier observations of the effect[7] but surpasses them in clarity and precision.

The electromagnetic nature of the production is again demonstrated in the departure of this ratio from unity. The agreement with expectations based on $q\bar{q}$ annihilation is excellent.

(d) Relative Production in pp and πp Interactions. In the Drell-Yan model, μ-pair production in pp interactions can occur only by virtue of the antiquarks in the nucleon sea. On the other hand, in πp interactions a valence antiquark is available from the pion. Since the nucleon's sea distribution falls much more rapidly with x than its valence distribution, one expects that $\sigma(\pi N)/\sigma(pN)$ should become very large as x_2 (x of target quark) becomes large. In order to increase x_2, according to the kinematics given in Fig. 3, one should fix x_F (equivalently y) and increase M. Figure 7, from the CIP experiment, shows this cross section ratio at fixed y plotted for increasing M. The ratio rises to over 100 at a mass of 10 GeV.

To summarize these comparisons, the data are in good qualitative agreement with expectations of the production via $q\bar{q}$ annihilation. Note however that the comparisons are often integrated over x_F and P_T so that in particular kinematic regions other effects may be dominant.

Next we turn to more quantitative consideration of the data with an eye to extracting information on hadron structure.

IV. Quantitative Comparisons and Structure Function Measurements

(a) Proton-induced Pairs.

Consider first, data on $p+p \rightarrow \ell^+ + \ell^- + \ldots$ Here one can make direct comparison with the quark distribution obtained in lepton scattering experiments.

There are three recent experiments at the CERN ISR as shown in Table I. Two of the experiments detect electron-pair final states while one detects muon-pairs. Since systematic effects are quite different for these two final states, agreement in the measured cross sections adds considerable confidence to the results. Figure 8 shows the results for $d\sigma/dMdy\big|_{y=0}$. As one can see, within the quoted errors of ~15%, there is excellent agreement.

It is interesting to use these data to test the scaling prediction of the Drell-Yan model, namely that $M^3 d\sigma/dM$ or equivalently $M^3 d\sigma/dMdy\big|_{y=0}$ is a function only of $M/\sqrt{s}$. Figure 9 shows the comparison of the ABC experiment at four ISR energies with results of the CFS group at Fermilab. Scaling appears to be satisfied within the precision of the data comparison.

Two comments are in order here. First, although the data are consistent with scaling down to $M/\sqrt{s} \sim 0.1$, it would be premature to conclude that the Drell-Yan mechanism accounts for all the production here. Similar scaling effects have also been seen in resonance production.[8] Second, if one is to learn about the QCD corrections to the Drell-Yan mechanism by studying scale breaking effects, high precision and large variation of M at fixed τ is required since violations are expected to be logarithmic in M. For example, at $M/\sqrt{s} = 0.2$, the cross section is expected to change by ~15% when M varies from 4 to 10 GeV.

The highest precision data on proton production of μ-pairs comes from the CFS experiment. Thus it is especially interesting to compare their results for the antiquark distribution in the nucleon with that deduced from neutrino scattering.

For their analysis they use lepton scattering measurements of $\nu W_2(x, Q^2)$ to characterize the valence quark distributions[9] and they deduce sea quark distributions. Their data suggest an SU(3) non-symmetric sea and leads to the distributions given in Table 3. The result to be compared with neutrino scattering results is

$$\bar{q}(x) = \bar{u}(x) + \bar{d}(x) + \bar{s}(x).$$

The obvious assumption here is that the same structure functions measured in lepton scattering with space like Q^2 can be used to describe this time-like process, and can be applied with the substitution $|Q^2|=M^2$. This procedure has been justified by analyses of the leading order QCD terms which correct the basic $q\bar{q}$ process.[10] Higher order terms have also been considered and the results here will be discussed in a few moments.

Figure 4 shows the comparison of the CFS pair production results for $\bar{q}$ with that obtained in the neutrino experiments. There is the suggestion of a normalization shift between the two sources and the agreement is better if the ν result is scaled up by a factor of ~ 1.5. There are two caveats to keep in mind in this comparison. First the Q^2 range of the two experiments and the dependence Q^2 on x differs in the two experiments. Second the quoted systematic uncertainty in the CFS experiment is ~ 20%.

A second experiment has recently reported results on proton production of μ-pairs. In the CERN CCOPS experiment they try to represent their observed $d^2\sigma/dMdx_F$ spectra using the CDHS determinations of valence and sea quark distributions from neutrino scattering. They find a good agreement of the observed shape with the prediction of the simple Drell-Yan model, although an overall scale factor must be applied to the absolute normalization. They find

$$\left(\frac{d^2\sigma}{dMdx_F}\right)_{\text{OBS}} = K \left(\frac{d^2\sigma}{dMdx_F}\right)_{\substack{\text{PREDICTED}\\ \text{FROM}\\ \text{CDHS}}}$$

with $K = 2.1 \pm 0.3$.
The effect is similar to that seen in the CFS experiment.

There have been several recent theoretical analyses which have attempted to evaluate higher order QCD corrections to the simple Drell-Yan mechanism.[10] These analyses reach the conclusion that at Q^2 values of present experiments the process $q\bar{q} \to g\gamma^*$ is important and contributes differently in the deep inelastic lepton scattering than in pair production. They find that the shape of the observed distributions should be only slightly affected but the overall normalization should change by ~ 1.8, i.e.

$$\left(\frac{d\sigma}{dM}\right) \sim 1.8 \left(\frac{d\sigma}{dM}\right)_{\substack{\text{SIMPLE}\\ \text{DRELL-YAN}}}$$

Hence a very critical issue in this field is to assess whether or not the observed normalization shift corresponds to the theoretically predicted effect.

(b) Pion-induced Pairs.

We turn now to muon pair production by pions. Here one no longer has a test of the Drell-Yan formalism but instead a determination of the quark distribution in the pion.

There are 4 experiments which have made recent contributions to this field. The CCOPS experiment at CERN and the CPI experiment at Fermilab are very similar in character. The CERN SISI experiment uses an open geometry having no hadron shield. Here they have better mass resolution but at the expense of lower event rates. At Brookhaven the BRF group has done a beam dump experiment using incident pions of 16 and 22 GeV.

All four experiments have determined a pion structure function from their data. For the first 3 experiments, which are at similar energies, the resulting shapes are shown in Fig. 10. Thus to the extent that these shapes must have a normalization giving two valence quarks in the pion, the experiments agree. As we will discuss in a moment, however, there is a discrepancy in how they arrive at the final normalization.

The pion quark distribution obtained in the BNL experiment is shown in Fig. 11. Owens and Reya[11] have predicted very substantial scale breaking effects in this distribution and when their calculation, together with the BNL measurement is used to infer what to expect at higher incident energies, the results agree well with the CPI determination.

The important conclusion to be drawn from these measurements is that it is substantially easier to find a high energy quark in a pion than in a nucleon. One finds an x distribution of ~ $(1-x)^1$ in pions and ~$(1-x)^3$ in nucleons.

The resulting shape of the pion quark distribution agrees with a naive application of the quark counting rules but a more careful analysis which includes spin considerations predicts[12] a shape like $(1-x)^2 + a/M^2$. The CPI experiment is the only one so far reporting a comparison with this form and while they are consistent with such a parameterization, their data are insensitive to the M dependence of the x-independent term.

We have seen that for proton induced pairs there is evidence for an overall normalization shift between the simple Drell-Yan cross section and what is actually observed. What is the case for pion induced pairs?

To compare the absolute normalizations obtained in the 3 high energy experiments we show in Fig. 12 their results for J/ψ production. The quantity plotted in Fig. 12 is the cross section per nucleon, and since all experiments use heavy nuclear targets a knowledge of the cross section A-dependence is needed. The NA-3 experiment used a small hydrogen target together with their platinum target and measures $\sigma_{J/\psi} \propto A^{0.95\pm0.03}$. The SISI experiment used a beryllium target and assumed $\sigma_{J/\psi} \propto A^{1.0}$. The CPI experiment used carbon and copper targets in addition to the primary tungsten target and measures $\sigma_{J/\psi} \propto A^{0.96\pm0.07}$. Thus all experiments agree on their normalization and A-dependence of J/ψ production.

In the case of the μ-pair continuum, however, the NA-3 experiment measures $\sigma \propto A^{1.03\pm0.03}$ while CPI finds $\sigma \propto A^{1.12\pm0.05}$. This difference leads to an overall shift in cross sections per nucleon of 1.8.

Thus the CPI experiment finds an acceptable normalization for the pion's valence quark distribution function without an extra scale factor (i.e. K=1), while the NA-3 experiment concludes that K=2.2±0.3 if the quark distribution function is to be normalized to 1.

The implication here is that a knowledge of A-dependence affects is crucial if one is to interpret the results obtained from the heavy targets used in all these experiments.

V. QCD Modifications of Drell-Yan

We have seen that $q\bar{q}$ annihilation appears to be the dominant source of high mass μ-pairs. Departures from this simple mechanism are predicted by QCD.

One area where QCD subprocesses are believed to play a significant role is in producing the fairly large P_T values seen for the pairs.[13] Let's look at the currently available experimental facts. Fig. 13 shows $\langle P_T \rangle$ as a function of pair mass for both proton and pion induced pairs. The variation of $\langle P_T \rangle$ for different center of mass energies is given in Fig. 14. The trends are those predicted by QCD, but some amount of intrinsic quark P_T must be folded in and its magnitude may vary with the x of the quark.[14] The main comparisons to date are in terms of $\langle P_T \rangle$ or $\langle P_T^2 \rangle$. More detailed comparisons such as the shape of the P_T spectrum at large P_T and the helicity angular distributions of the pairs are needed before one can say with confidence that the high P_T production is thoroughly understood in terms of the presently proposed QCD mechanisms.

Another kinematic region where QCD is expected to produce substantial departure from the simple Drell-Yan process is for pion production of pairs at large x. Berger and Brodsky have argued that in this kinematic region the antiquark from the pion is far off shell and that this leads to longitudinal polarization of the virtual photon.[15] The way to detect this is to fit the data as $d\sigma/d\cos\theta^* \propto 1+\alpha\cos^2\theta^*$. As can be seen from equation (1) after integration over ϕ^*, $\alpha=(W_T-W_L)/(W_T+W_L)$ and $\alpha\neq1$ indicates a non-zero value for the longitudinal structure function W_L.

Results from the CPI experiment for α as a function of the x of the annihilating quark from the pion are shown in Fig. 15. The solid line is the prediction of Berger and Brodsky.

This then is a summary of the current situation in lepton pair production by hadrons, from an experimentalist's point of view. I think it is clear that the field is active and evolving. There remain important issues on both the experimental and theoretical side which deserve further clarification and development. There is every indication that continued work will bear fruit. Our experimental capabilities are not yet fully exploited nor is the ingenuity of our theoretical colleagues.

References

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TABLE I(a) Recent Contributions

	Reaction	$\sqrt{s}$	Mass Range (Continuum)	x_F Range	Events	$\sigma_{M/M}$
CERN-ISR ABC (Willis)	$pp\to e^+e^-+\ldots$	64	4 - 17	±0.2	~1000	4%
CCOR (DiLella Comilleri)	e^+e^-	64	6.5 - 14	±0.2	~ 130	4%
CHFMNP (Belletini Ting)	$\mu^+\mu^-$	64	5 - 17	-0.1 to .5	1300	11%
CERN-SPS CCOPS-NA3 (Michellini)	$\begin{pmatrix}\pi^+\\ \pi^-\\ p\end{pmatrix} N\to\mu^+\mu^-$	19,23	4 - 12	- .3 to 1.	$\left.\begin{matrix}\pi^+ 2200\\ \pi^- 5900\end{matrix}\right\}\sqrt{s}=19$ $\pi^-5700]\sqrt{s}=23$	4.5%
SISI	$\pi^-N\to\mu^+\mu^-$	17	3.8 - 7.8	- .1 to .8	500	1.5%
FERMILAB CFS (Lederman)	$pN\to\mu^+\mu^-$	19 24 27	5 - 17	.3 to .6 .1 to .4 -.15 to .075	180,000	2%
CIP (Pilcher Smith)	$\begin{pmatrix}\pi^-\\ \pi^+\\ p\end{pmatrix} N\to\mu^+\mu^-$	21	4 - 10	0 to 1.	2200 400 200	4%
BNL BRF (Mellisinos)	$\pi^-N\to\mu^+\mu^-$	5.5 6.4	1.4 - 2.7	.2 to 1.	6800 1600	10%

TABLE I(b) Key to Collaboration Acronyms

ABC	Athens, Brookhaven, CERN
BRF	Brookhaven, Rochester, National Science Foundation
CCOPS (NA-3)	CERN, College de France, Orsay, Ecole Polytechnique, Saclay
CCOR	CERN, Columbia, Oxford, Rockefeller
CFS	Columbia, Fermilab, Stony Brook
CHFMNP	CERN, Harvard, Frascati, MIT, Naples, Pisa
CIP	Chicago, Illinois, Princeton
SISI	Saclay, Imperial College, Southampton, Indiana

TABLE II

Reaction	Experimental Group	α
πN	CCOPS	0.80±0.17
	CIP	1.17±0.29
pN	ABC	1.15±0.34
	CHFMNP	1.0 ±0.3

TABLE III CFS Results on Antiquark Sea Distributions

(a) asymmetric sea (favored by the data)

$$\bar{u}/\bar{d} = (1-x)^{3.1\pm0.4}$$

$$\bar{d} = 0.62\pm0.02(1-x)^{8.0\pm0.1}$$

$$\bar{s} = (\bar{u}+\bar{d})/4$$

(b) symmetric sea

$$\bar{u} = \bar{d}$$

$$= 0.56\pm0.01\ (1-x)^{9.0\pm0.1}$$

$$\bar{s} = (\bar{u}+\bar{d})/4$$

NOTE: Errors quoted here are only statistical.

Questions and Comments for the Talks of Kienzle and Pilcher

Q. (Cox, Fermilab) Could W. Kienzle comment on the A-dependence?

A. (Kienzle) The number which I gave was alpha = 1.03±0.03 between hydrogen and platinum. You should also ask somebody of the CFS collaboration to comment on their A-dependence which gave for protons on three nuclear targets (Be, Cu, Pt), α = 1.01±0.03. Our own data are consistent with alpha = 1. For the A-dependence measurement, the hydrogen data are integrated over the mass region 4 to 8.5 GeV.

Comment (Pilcher) One point to make is that the quark composition of a target is important in this production so that if one is using hydrogen for determining the A-dependence some correction has to be made for the quark composition of the target. I think what has been done by the NA3 experiment is very reasonable but is slightly model dependent.

Comment (Kienzle) By using the difference between the measured π^+ and π^- cross sections, one is independent of any sea contribution so the correction is quite straightforward. In the case of the heavy targets, one also has an isospin asymmetry to be corrected. Can I ask, in the CIP experiment, how much does this correction change the α value?

A. (Pilcher) We estimated the correction and found it to be small compared with the experimental error so there is no explicit correction made. That wouldn't account for the difference in the two measurements.

Q. (Yoh, Columbia) Do you get the factor K for hydrogen only? What kind of errors do you get from that?

Note added in proof: Although this result was not available at the time of the conference, a subsequent analysis of the $\pi^- H_2$ data gave K = 2.4±0.5.

Q. (Selove, Pennsylvania) Did the CCOP and the CIP experiments use comparable heavy nuclei, and if so, how did the measured cross sections per nucleus compare?

A. (Pilcher) One of the experiments used primarily tungsten while the other used platinum. The cross sections per nucleus agree to within the estimated systematic errors of 20-30%.

Q. (Selove, Pennsylvania) I don't understand how one obtains the K factor in the pion nucleon case where the pion structure function is also being determined.

A. (Kienzle) The normalization of the pion's valence quark distribution is fixed to give 2 valence quarks. The nucleon quark distribution function is the one of CDHS which is in good agreement with our results from the proton nucleon data. I might add here that the quark distribution functions are better determined when the particle under study is the projectile rather than the target. This arises because of acceptance considerations.

Comment (Selove) It might be of use to remark that in a totally separate type of experiment looking at hadron jets, the structure function of the pion has also been determined with an accuracy that is thought to be something like 20% and it agrees within about 20% with the numbers reported by Pilcher in his publication. I don't know where this factor of 2 in the QCD predictions will end up but that is just simply an experimental fact.

Comment (Melissinos, Rochester) I would like to point out that the pion structure function measured in the CIP CERN experiments are really an average over a very broad range of q^2. They range from q^2 = 16 to q^2 = 64 and theoretically the structure function changes very rapidly over that range. Therefore, any careful analysis obviously has to be done in separate mass intervals.

Q. (Raja, Fermilab) Do you have a value for the $\bar{p}$ to proton ratio for psi production cross sections at 200 GeV?

A. (Kienzle) I think it is something like a factor of 1.4. We have all the possible particle ratios for the J/ψ production on platinum and also on hydrogen. So, if you contact us later, we can give you more detailed informaion on the J/ψ since there is really a large amount of data.

Q. (Smith, Princeton) It is obvious looking at this that there is finally becoming some $\bar{p}$ data available. It seems like the one experiment everybody would love to do, or to have done. I was just wondering if Dr. Cox would comment on the future experiment at Fermilab? What data should we expect on $\bar{p}$ induced events in the reasonable future?

A. (Cox, Fermilab) Since this is a comment for our plans for antiprotons, I think with our $\bar{\Lambda}$ into $\bar{p}$ beam we should be able to get somewhere between 1000 and 2000 $\bar{p}$ events between 4 and 9 GeV. I think this is fairly comparable to the Chicago-Princeton-Illinois data for π^- and I expect that we should be able to answer, along with NA3, quite definitely the question of the absolute level of dimuon production by hadrons.

A. (Kienzle) We are very much aware of the importance of $\bar{p}$ induced dimuon events in view of this scale factor K. In the proton nucleon case the cross section is given by valence-sea terms, therefore the cross section is proportional to the amount of anti-sea quarks. In our case, we have used an SU(3) asymmetric sea as most people are doing now (e.g. as found by the CDHS collaboration). If one uses antiprotons, this question of the scale factor K becomes independent of the sea since production is mainly through valence-valence terms.

We have thus been concentrating on collecting $\bar{p}$ data for one 30-day run and we are taking a second run starting in September under very carefully controlled flux conditions. So far we have obtained about 200 $\bar{p}$ events. About 50 of them at 200 GeV are analysed and give a scale factor 2.3. Eventually we will have a total of between 300 and 400 $\bar{p}$ induced events in the dimuon continuum. This will be in addition to a sample of almost 1000 K^- events to measure the K^- structure function.

The measurement of at least several hundred antiproton-induced muon pairs is desirable not only for the total cross section in itself but to find out where this K factor comes from. It is necessary to have enough data to distinguish whether there is a difference in the shape of the structure functions between Drell-Yan and deep inelastic lepton scattering, or whether this correction to the naive Drell-Yan model can be expressed as a constant scale factor. We would like to have enough data to be able to measure the x distributions and to determine the parameters alpha and beta in the Buras-Gaemers parametrization of the $\bar{p}$ structure functions.

Comment (Ellis, CERN) First I would like to make it clear that I am not the Ellis that Pilcher quoted. That is Keith Ellis from MIT. Perhaps I could try to respond to these questions about the K factor in QCD. As far as I am aware, there is now more or less consensus among the theoreticians on the renormalization factor that you get if you do the first order radiative corrections in QCD. Now that correction is of the effect to change the cross section from 1 to 1 + 1. Now that second one is somewhat m^2 dependent, x_f-dependent, and so forth. Now clearly, once you find 1 + 1 you wonder what the next term is going to be. I think that the theoretical work on the first order radiative correction has been done but now a lot of thinking has to be done whether it is possible to do any sort of exponentiation for the higher order terms. Just one other comment which I might make is that somebody mentioned doing large p_t. I am sure that there will be a corresponding change of the normalization of the cross section there. There is no reason why that K should be 2. The complete calculations have not been done. I know that some people are doing it but they are very long and complicated.

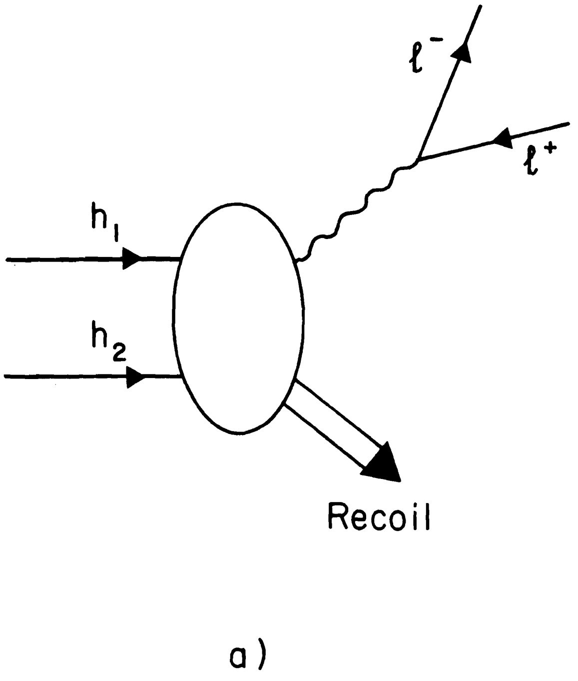


Fig. 1. Schematic representation of:
a. lepton pair production

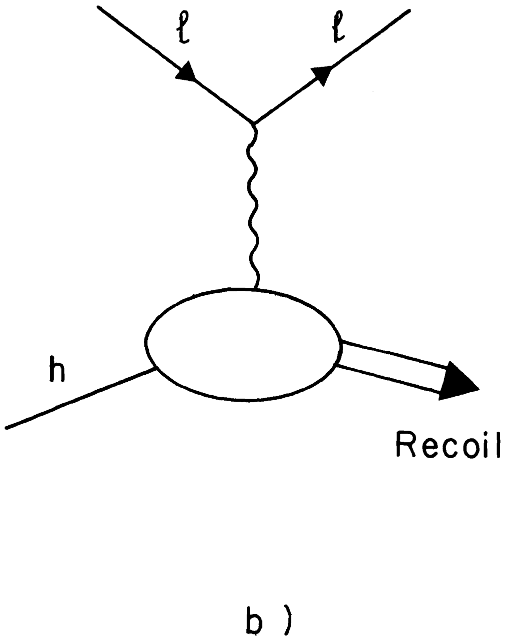


Fig. 1. Schematic representation of:
b. deep inelastic lepton scattering.

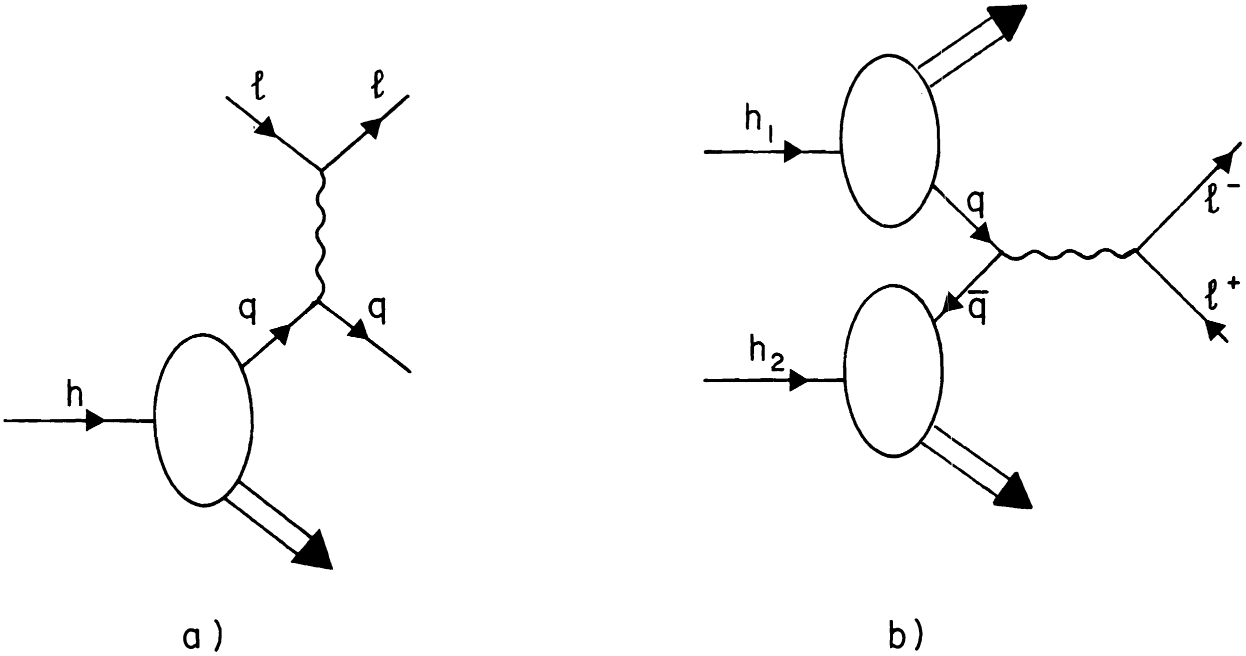
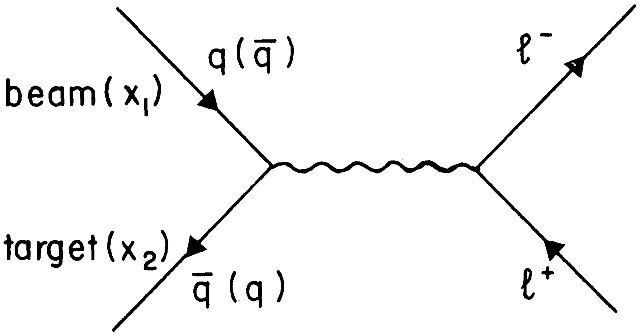


Fig. 2. Quark model mechanisms for:
(a) deep inelastic lepton scattering,
(b) lepton pair production



$$x_1 x_2 = M^2/S$$

(neglecting quark P_T and mass)

$$x_1 - x_2 = x_F$$

Fig. 3. Kinematics for $q\bar{q}$ annihilation.

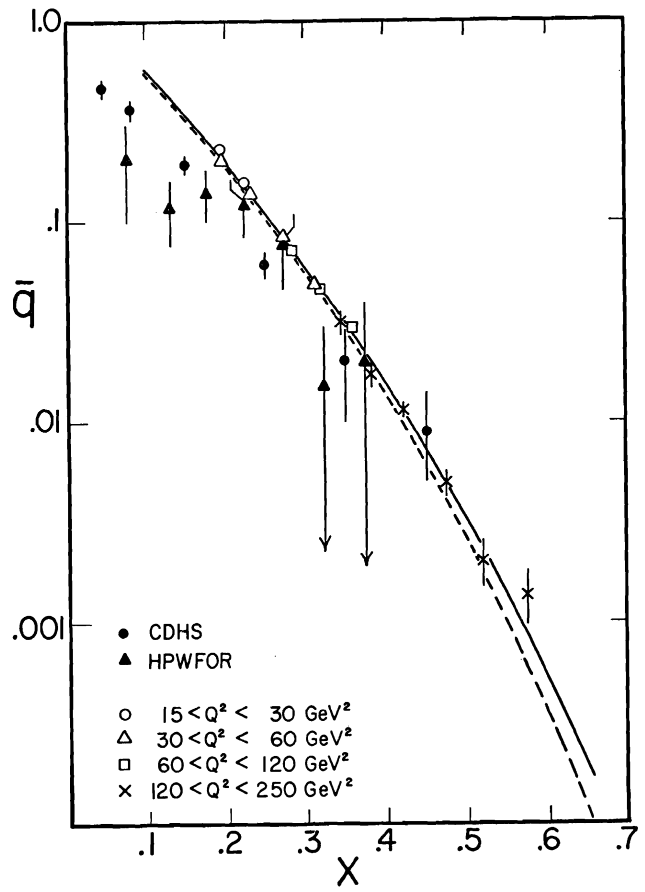


Fig. 4. Comparison of anti quark distribution in the nucleon as determined in deep inelastic neutrino experiments (solid circles and triangles) and in lepton pair production by the CFS group.

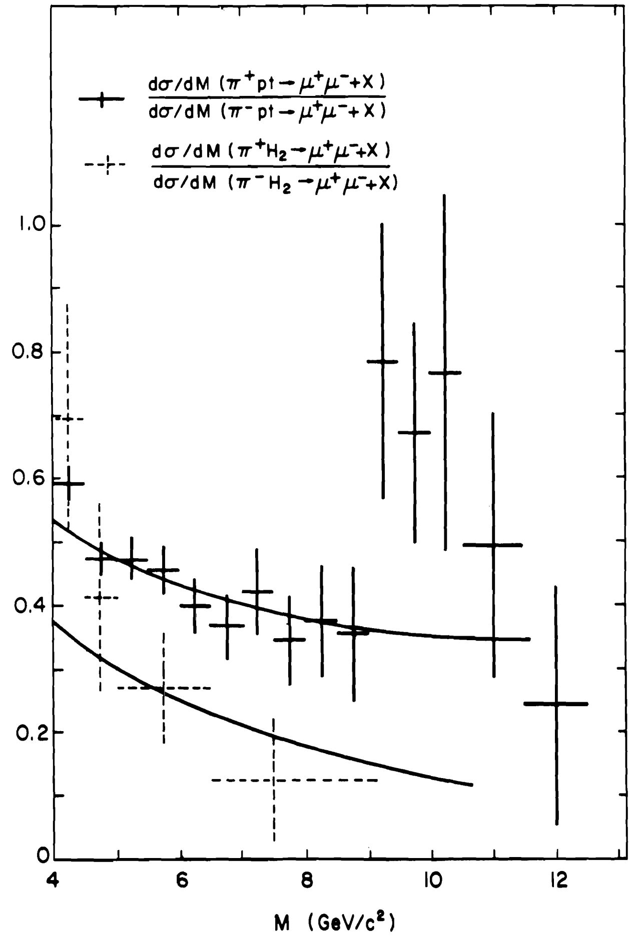


Fig. 6. Ratio of continuum μ-pair production by π^+ and π^- as a function of mass (CCOPS group).

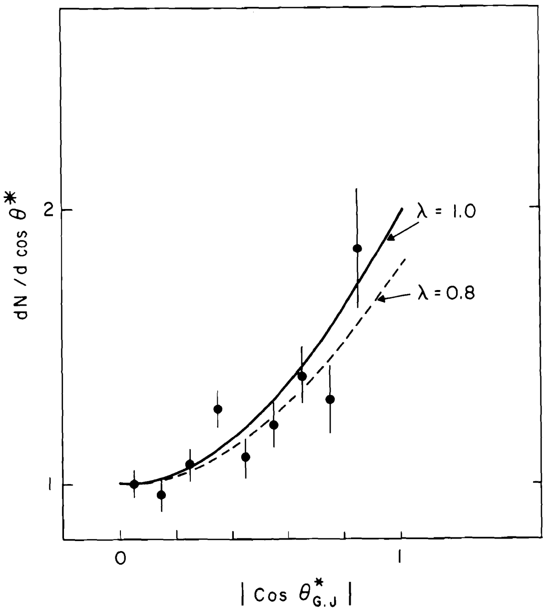


Fig. 5. Helicity angular distribution dN/dcos θ* for continuum μ-pair production by pions as measured by the CCOPS group.

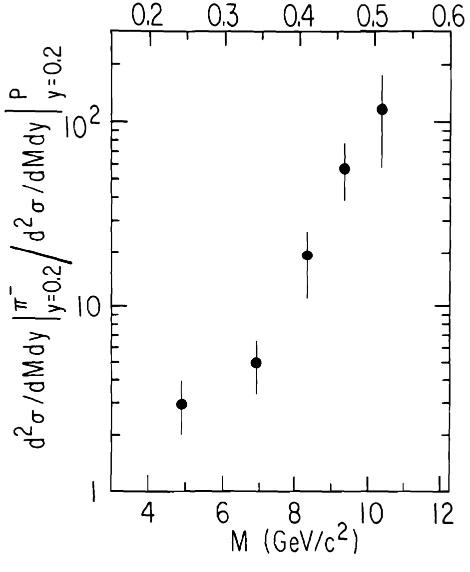


Fig. 7. Ratio of continuum μ-pair production by π^- to p as a function of pair mass.

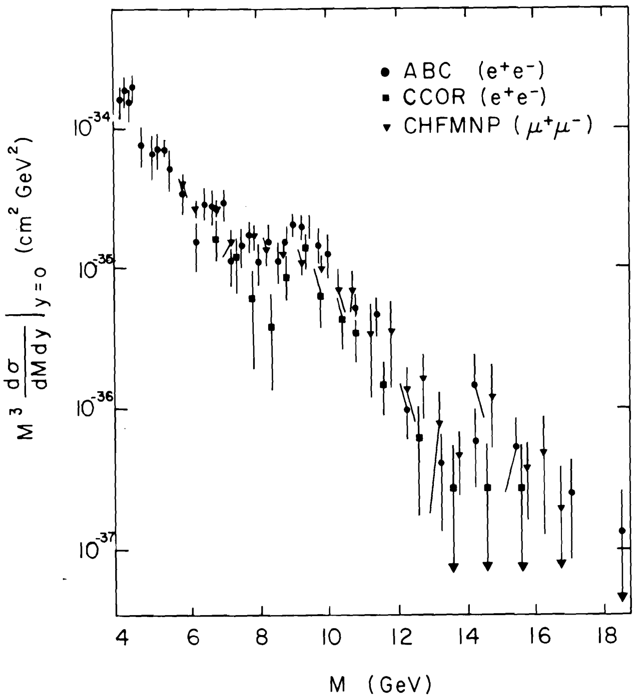


Fig. 8. Comparison of recent ISR data on $d\sigma/dMdy\,|_{y=0}$ versus mass.

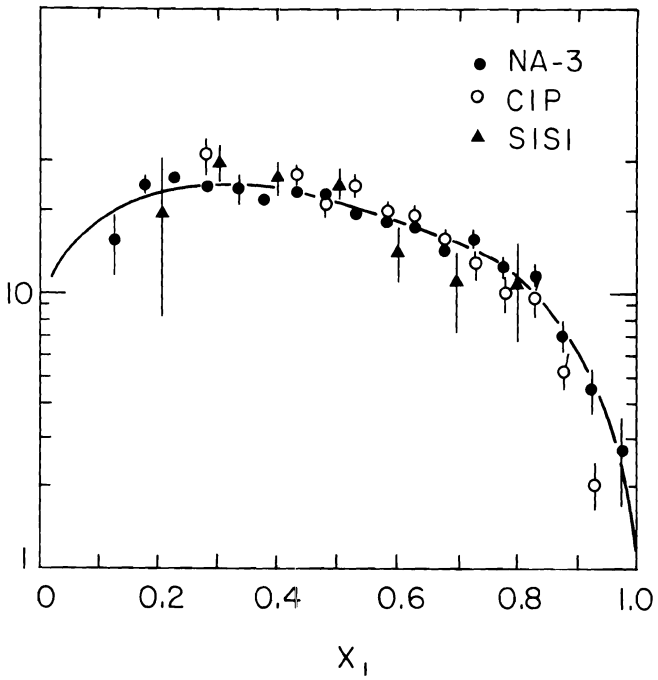


Fig. 10. Shapes of the pion structure function as inferred from a Drell-Yan analysis in three recent high energy experiments. Note that the same normalization has been applied to each experiment.

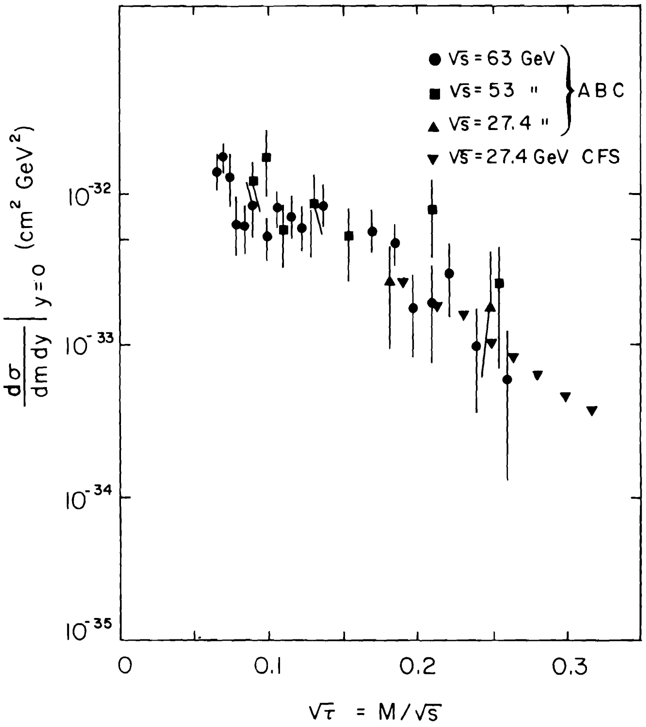


Fig. 9. Scaling comparison of ISR and Fermilab data.

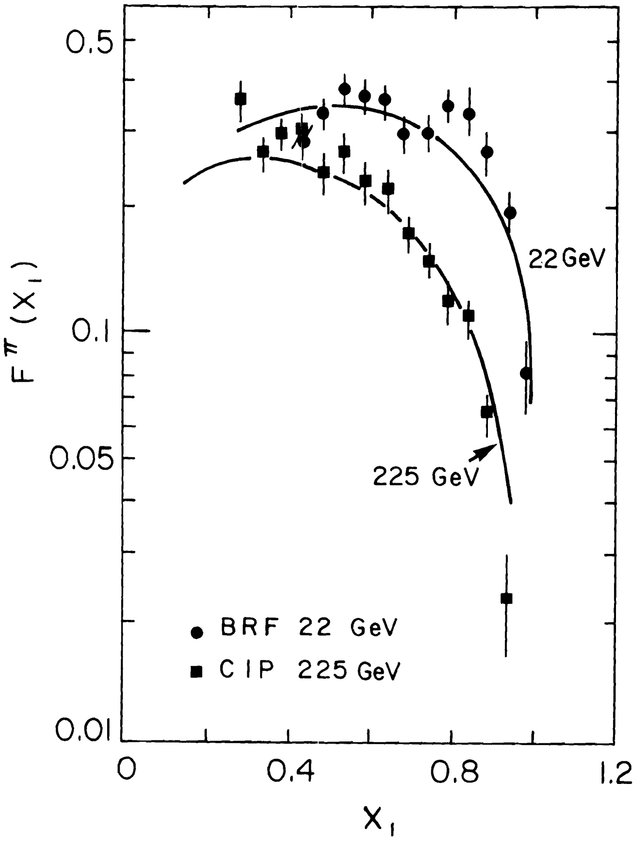


Fig. 11. The pion structure function from the BRF group with 22 GeV pions. The solid curves show the scale breaking predicted by Owens and Reya between the 22 and 225 GeV experiments.

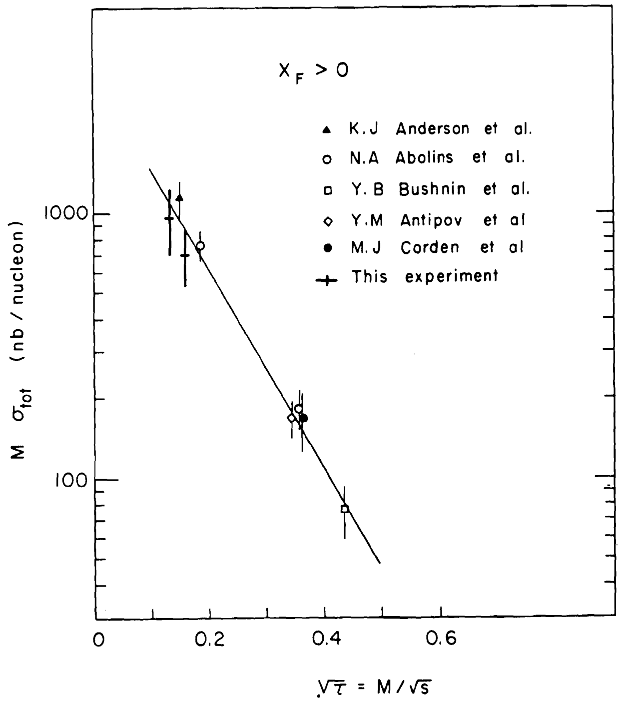


Fig. 12. J/ψ production cross section per nucleon.

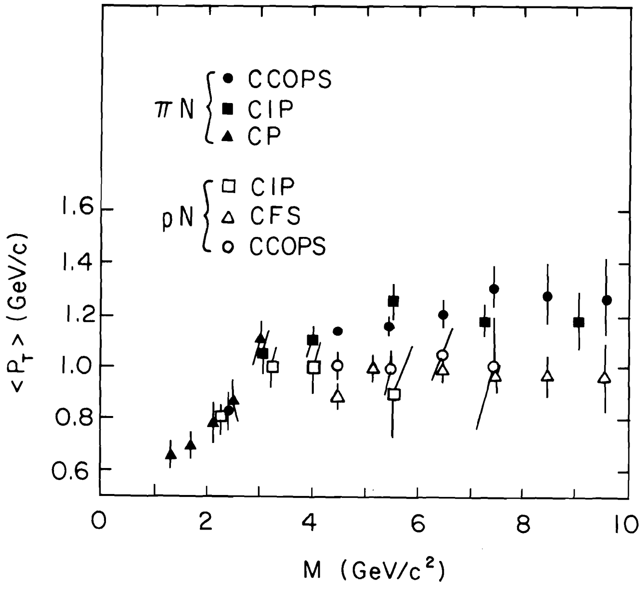


Fig. 13. Mean transverse momentum for pion and proton induced pairs as a function of pair mass.

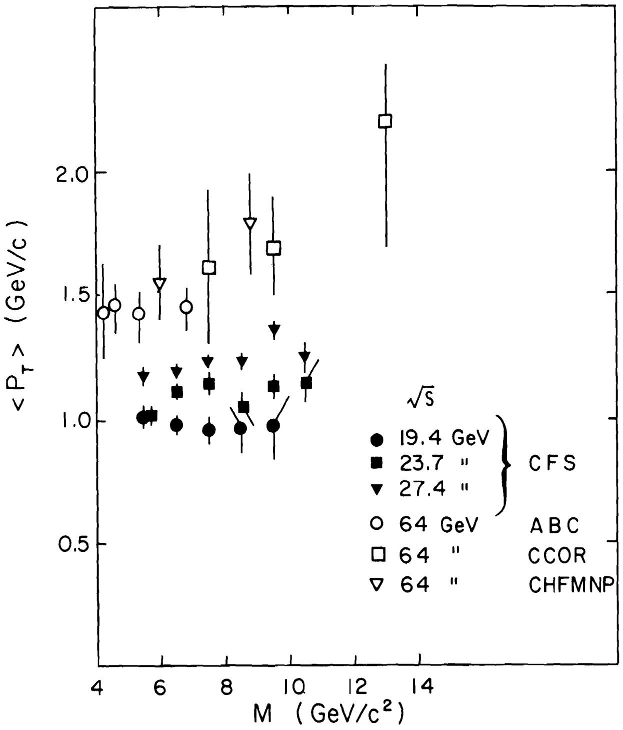


Fig. 14. Mean transverse momentum of proton induced pairs for different CM energies.

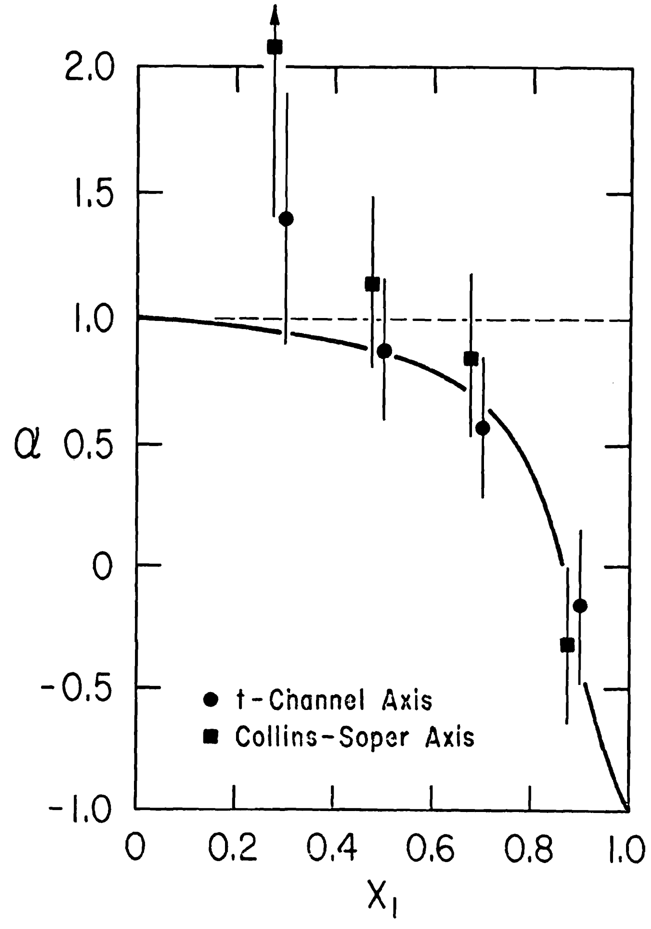


Fig. 15. Results for α from a fit of the helicity angular distribution dN/dcos θ *∝ 1 + αcos^{2}θ * in different x intervals.